INTRODUCTION TO Materials Science FOR Engineers

SECOND EDITION

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Macmillan Publishing Company
New York
Collier Macmillan Publishers
London

TABLE 11.1-1 Electrical Conductivities of Some Materials at Room Temperature

Conducting Range	Material	Conductivity, σ ($\Omega^{-1} \cdot m^{-1}$)
Conductors	Aluminum (annealed)	35.36×10^6
	Copper (annealed standard)	58.00×10^6
	Iron (99.99 + %)	10.30×10^6
	Steel (wire)	$5.71–9.35 \times 10^6$
Semiconductors	Germanium (high purity)	2.0
	Silicon (high purity)	0.40×10^{-3}
	Lead Sulfide (high purity)	38.4
Insulators	Aluminum oxide	$10^{-10}–10^{-12}$
	Borosilicate glass	10^{-13}
	Polyethylene	$10^{-13}–10^{-15}$
	Nylon 66	$10^{-12}–10^{-13}$

Source: Data from C. A. Harper, ed., *Handbook of Materials and Processes for Electronics*, McGraw-Hill Book Company, New York, 1970; and J. K. Stanley, *Electrical and Magnetic Properties of Metals*, American Society for Metals, Metals Park, Ohio, 1963.

The drift velocity is in units of m/s, and the electric field strength ($E = V/\ell$) in units of V/m.

When both positive and negative charge carriers are contributing to conduction, Equation 11.1-4 must be expanded to account for both contributions:

$$\sigma = n_n q_n \mu_n + n_p q_p \mu_p \qquad (11.1\text{-}6)$$

The subscripts n and p refer to the negative and positive carriers, respectively. For electrons, electron holes, and monovalent ions, the magnitude of q is 0.16×10^{-18} C. For multivalent ions, the magnitude of q is $|Z_i| \times (0.16 \times 10^{-18}\ \text{C})$, where $|Z_i|$ is the magnitude of the valence (e.g., 2 for O^{2-}).

Table 11.1-1 lists values of conductivity for a wide variety of engineering materials. It is apparent that the magnitude of conductivity produces distinctive categories of materials consistent with the types outlined in Chapters 1 and 2. We shall discuss this electrical classification system in detail at the end of this chapter (Section 11.7). But first, it is necessary to look at the nature of electrical conduction in order to understand why conductivity varies by more than 20 orders of magnitude among common engineering materials.

Sample Problem 11.1-1

A wire sample (1 mm in diameter by 1 m in length) of an aluminum alloy (containing 1.2% Mn) is placed in an electrical circuit such as that shown in Figure 11.1-1. A voltage drop of 432 mV is measured across the length the wire as it carries a 10-A current. Calculate the conductivity of this alloy.

Sample Problem 11.4-2

The polarization for a ferroelectric is defined as the density of dipole moments. Calculate the polarization for tetragonal $BaTiO_3$.

Solution

Using the results of Sample Problem 11.4-1(a) and the unit cell geometry of Figure 11.4-3, we obtain

$$P = \frac{\Sigma\, Qd}{V}$$

$$= \frac{10.56 \times 10^{-30}\ \mathrm{C \cdot m}}{(0.403 \times 10^{-9}\ \mathrm{m})(0.399 \times 10^{-9}\ \mathrm{m})^2}$$

$$= 0.165\ \mathrm{C/m^2}$$

11.5 Semiconductors

The magnitudes of conductivity in the semiconductors in Table 11.1-1 fall within the range 10^{-4} to $10^{+4}\ \Omega^{-1} \cdot \mathrm{m}^{-1}$. This intermediate range corresponds to band gaps of less than 2 eV. As shown in Figure 11.2-8, both conduction electrons and electron holes are charge carriers in a simple semiconductor. For the example of Figure 11.2-8 (pure silicon), the number of conduction electrons is equal to the number of electron holes. Pure, elemental semiconductors of this type are called *intrinsic semiconductors*. This is the only case we shall deal with in this chapter. In Chapter 12, the important role of impurities in semiconductor technology will be demonstrated in our discussion of *extrinsic semiconductors*, semiconductors with carefully controlled, small amounts of impurities. For now, we can transform the general conductivity expression (Equation 11.1-6) into a specific form for intrinsic semiconductors:

$$\sigma = nq(\mu_e + \mu_h) \qquad (11.5\text{-}1)$$

where n is the density of conduction electrons (= density of electron holes), q the magnitude of electron charge (= magnitude of hole charge = 0.16×10^{-18} C), μ_e the mobility of a conduction electron, and μ_h the mobility of an electron hole. Table 11.5-1 gives some representative values of μ_e and μ_h together with E_g, the energy band gap and the carrier density at room temperature. Inspection of the mobility data indicates that μ_e is consistently higher than μ_h, sometimes dramatically so. The conduction of electron holes in the valence band is a relative concept. In fact, electron holes exist only in relation to the valence electrons; that is, an electron hole is a missing valence electron. The movement of an electron hole in a given direction is simply a representation that valence electrons have moved in the opposite direction (Figure 11.5-1). The cooperative motion of the valence electrons (represented by μ_h) is an inherently slower process than the motion of the conduction electron (represented by μ_e).